



EDITED BY

PAUL E. HATCHER AND  
ROBERT J. FROUD-WILLIAMS

# WEED RESEARCH

Expanding Horizons

WILEY

# **Weed Research**

Expanding Horizons

*Edited by Paul E. Hatcher and Robert J. Froud-Williams*

*University of Reading, Reading, UK*

**WILEY**

## 9

## Non-Chemical Weed Management

Bo Melander<sup>1</sup>, Matt Liebman<sup>2</sup>, Adam S. Davis<sup>3</sup>, Eric R. Gallandt<sup>4</sup>,  
Paolo Bàrberi<sup>5</sup>, Anna-Camilla Moonen<sup>5</sup>, Jesper Rasmussen<sup>6</sup>,  
Rommie van der Weide<sup>7</sup> and Francesco Vidotto<sup>8</sup>

<sup>1</sup> Department of Agroecology, Aarhus University, Slagelse, Denmark

<sup>2</sup> Department of Agronomy, Iowa State University, Ames, Iowa, USA

<sup>3</sup> Global Change and Photosynthesis Research Unit, US Department of Agriculture–Agricultural Research Service, Urbana, Illinois, USA

<sup>4</sup> School of Food and Agriculture, University of Maine, Orono, Maine, USA

<sup>5</sup> Institute of Life Sciences, Scuola Superiore Sant'Anna, Pisa, Italy

<sup>6</sup> Department of Plant and Environmental Sciences, University of Copenhagen, Taastrup, Denmark

<sup>7</sup> Department of Applied Plant Research, Wageningen University and Research Centre, Lelystad, The Netherlands

<sup>8</sup> Department of Agriculture, Forest and Food Sciences, University of Torino, Grugliasco, Italy

## Introduction

Non-chemical weed management covers all management practices that influence weeds except herbicides. This chapter focuses on preventive, cultural and direct physical weed control methods. Preventive methods reduce weed germination, cultural methods improve crop competition and direct physical weed control reduces weed survival. Before the discovery of selective herbicides, weeds were managed by non-chemical methods, but herbicides more or less eliminated non-chemical weed management in the last part of the twentieth century. Herbicides became a stand-alone method against weeds until the appearance of public concerns about the adverse environmental effects of herbicides and the rise of organic agriculture.

Parallel to the political awareness about side-effects of herbicides and the need for regulations, an increasing conversion to organic farming has taken place, favourably subsidised by some European countries. Research projects have been funded to develop non-chemical weed management in horticultural and agricultural crops. Apart from scientific publications, most of the European work is discussed and disseminated through the European Weed Research Society working group on physical and cultural weed control ([www.ewrs.org/pwc](http://www.ewrs.org/pwc)). A wide range of direct physical methods (i.e. those used directly in the crop after it has been either transplanted or sown) have been introduced and studied, some of which employ new principles (e.g. automated intra-row cultivation), while others employ old principles (e.g. stubble cultivation) that have been



subjected to new research. Soon it became evident that physical weed control cannot act as a stand-alone treatment but had to be supplemented by preventive and cultural methods (Melander *et al.*, 2005). Preventive and cultural methods have thus been included in the research, with a particular interest in their interactions with direct methods.

In recent years, advanced technology, such as digital image processing for automatic steering systems for steerage hoes and global positioning system (GPS) for electronic mapping of crop seed positions for subsequent guidance of selective weeding devices, has developed in this area and opened up new perspectives for physical weed control. Among these innovations, robots for intra-row weeding in transplant vegetables are probably the most remarkable implements introduced recently for practical use (Melander *et al.*, 2015).

This chapter summarises the major achievements in European research, as well as work undertaken in North America. Research groups from both continents have interacted strongly on the topic over the years and shared common interests on the development of non-chemical tactics. The chapter encompasses preventive, cultural and direct weed control methods, explaining the basic principles and the integration of these tactics in weed management strategies for agricultural and horticultural crops and in some cases amenity areas as well.

## Preventive and Cultural Weed Control

Preventive and cultural approaches for weed control complement direct approaches that are based on herbicides and physical controls such as cultivation. These 'indirect' tactics for regulating weed populations are organised around three objectives: reducing weed density; reducing interference by surviving weeds against crops; and preventing undesirable shifts in weed population and community composition (Fig. 9.1).

In achieving these objectives, multi-tactic strategies that incorporate a range of preventive and cultural approaches, exploiting synergisms and complementarities among tactics, can be desirable for several reasons (Liebman & Gallandt, 1997). First, effective

Objectives	Reduce weed density	Reduce damage per surviving weed	Prevent undesirable shifts in the weed community
Principle(s)	<i>Disturbance niche elimination biocontrol</i>	<i>Competition</i>	<i>Diversity</i>
Practices ("Many little hammers")	<ul style="list-style-type: none"> <li>• Crop rotation</li> <li>• Cover cropping</li> <li>• Tillage</li> <li>• Mulching</li> <li>• Seed predation</li> </ul>	<ul style="list-style-type: none"> <li>• Crop spacing and density</li> <li>• Fertilizers and amendments</li> <li>• Intercropping</li> <li>• Cultivar choice</li> </ul>	<ul style="list-style-type: none"> <li>• Use many practices</li> <li>• A diverse crop rotation and cover cropping offer greater diversity of practices</li> <li>• Monitoring</li> <li>• Targeted eradication</li> </ul>

Fig. 9.1 Objectives, principles and practices for preventive and cultural weed control.



weed suppression can result from tactics whose individual impacts are weak but whose cumulative impacts are strong. Second, risks of crop failure or serious loss can be reduced when the burden of crop protection is distributed across many tactics. Third, the rate at which weeds adapt or evolve resistance to a given management tactic can be decreased when their exposure to that tactic is reduced. Here, we identify preventive and cultural approaches for weed management that are especially important and that can easily complement physical control tactics.

## Objectives, Principles and Practices

### Objective 1: Reduce Weed Density

Cropping system diversification through rotation can create a diversity of soil disturbance, planting and harvesting patterns that disrupt weed life-cycles and prevent any one weed species from becoming highly dominant. Long-term crop rotation studies in Sweden consisting of highly diversified crop sequences (6-year courses with five crops including grass leys) had no noteworthy weed problems after 26 years despite herbicides only being applied in 50–60% of the years (Andersson & Milberg 1996, 1998). Simple alternation of crops with contrasting characteristics may be insufficient to achieve weed control benefits. Anderson (2003) reported that weed density increased in rotations consisting of one cool-season crop followed by one warm-season crop (e.g. winter wheat–chick pea), whereas weed density decreased in rotations consisting of two different cool-season crops followed by two different warm season crops (e.g. pea–winter wheat–maize–soybean). Diversifying crops by including species with different planting dates within warm-season and cool-season categories enhanced the ability of the control tactics applied to control emerged weed seedlings, thus depleting the soil seed-bank while limiting the production of new seeds (Anderson, 2003). Schwarz and Moll (2010) showed in a German study that the inclusion of a perennial forage crop, repeatedly mown, could further reduce weed pressure as compared to rotations entirely composed of cash crops. The benefits of having perennial forage crops in crop sequences were also confirmed in a North American survey showing that, compared with cereal crops preceding cereals, lucerne hay crops preceding cereals lowered densities of the majority of both annual and perennial weed species (Ominski *et al.*, 1999). Particular crops select for and against particular weeds, however, and thus a complex rotation is needed to suppress a wide spectrum of weed species.

Various forms of tillage can be used to place weed seeds at particular locations in the soil profile, with concomitant effects on seed survival and seedling emergence ability (Mohler, 2001a). In general, weed seed vulnerability to seed predators and other mortality factors is greatest on the soil surface, whereas seedling emergence ability tends to decrease with increasing seed burial depth. Seed size can exacerbate the latter effect: smaller-seeded weed species are less likely to emerge from greater burial depths (Benvenuti *et al.*, 2001).

In cases where production of new seeds can be prevented, zero tillage can lead to large and rapid losses of weed seeds (Melander *et al.*, 2008; Jensen, 2009). Conversely, when production of new seeds does occur, deep tillage with an inversion plough can reduce weed densities due to inhibition of seedling emergence and on-going seed decay

(Mohler, 2001a). Zero-tillage systems involving direct seeding or transplanting into cover crop residues are being developed and tested for organic farming systems (Morse & Creamer, 2006).

Conservation biological control of weeds seeks to manipulate cropping system habitats with the goal of fostering natural enemies of weeds that can reduce weed densities over the longer term. Both vertebrate and invertebrate seed predators can be important in this regard (Westerman *et al.*, 2003; Gallandt *et al.*, 2005; Menalled *et al.*, 2006; Davis & Raghu, 2010). For example, including small grains, red clover and lucerne within maize- and soybean-based crop rotations can increase season-long seed predation rates by creating canopy cover and thus suitable habitat for insect and rodent seed predators at times when canopy cover of maize and soybean is low (Davis & Liebman, 2003; Heggenstaller *et al.*, 2006).

### **Objective 2: Reduce Damage Per Surviving Weed**

A competitive crop is often the first and best line of defence against weeds, which can achieve large size and great fecundity when interspecific competition is low. Management should always aim to maximise crop use of space and resources and to prevent weeds from occupying available niches.

Choice of row width may be dictated by the need to accommodate cultivation equipment, but if row width can be narrowed and crops sown in a more equidistant arrangement, weed suppression can be enhanced; this is especially true if crop densities can also be increased (Mohler, 2001b; Olsen *et al.*, 2005). Crop species for which this approach may be successful include maize, pea, rapeseed, small grain cereals and soybean. The use of increased crop density may not be an appropriate tactic for horticultural crops, since higher crop densities can translate into smaller size of individual harvestable units (e.g. potato tubers), with lower value. The competitive ability of horticultural crops can be increased greatly, however, by transplanting rather than direct seeding (Weaver, 1984). Increases in crop density may be economically disadvantageous if increased costs for seeds or transplants are not offset sufficiently by increases in crop yield and value (Kolb *et al.*, 2012).

Weeds can be highly responsive to soil fertility conditions, and the placement of synthetic fertilisers, especially N, at places and times that ensure greater access by crops than weeds can be a useful weed management tactic.

Organic farming systems put considerable emphasis on long-term transformations of soil conditions through the use of organic matter amendments, such as animal manures and composts, as well as crop residues (Gallandt, 2004). These amendments and the manner in which they are used can affect weeds and their interactions with crops. For example, band-injection of liquid manure into soil, rather than broadcast surface application, increased barley growth and competitive ability against weeds (Rasmussen, 2002). Weed biomass was lower and potato yields were higher in plots amended with legume residues, cattle manure and compost versus with barley residues and high rates of synthetic fertilisers (Gallandt *et al.*, 1998). However, organic matter amendments to soil may not always work to the benefit of weed management, nor do they obviate the need for effective control practices. In some cases, amendments can even improve weed fecundity and weed competitiveness against the crop (Liebman *et al.*, 2004; Menalled *et al.*, 2004).



Intercropping and living mulches combine two or more crops whose resource consumption patterns are physiologically, temporally or spatially complementary. Consequently, intercrops may use a greater share of available light, water and nutrients and produce greater yield per unit land area than at least one of the component crops in monoculture (Vandermeer, 1989; Willey, 1990). Greater resource use by intercrops than monocultures also can lead to improved opportunities for suppressing weeds through resource competition. For example, leek/celery intercrops were found to intercept more light earlier in the growing season and more effectively suppress *Senecio vulgaris* L. (groundsel) than did leek monocultures (Baumann *et al.*, 2000).

Crop cultivars vary in their ability to suppress weeds and to tolerate weed interference (Christensen, 1994; Lemerle *et al.*, 1996; Mohler, 2001b). Crop leaf angle, leaf area index, stature, canopy duration, maximal relative growth rate, allelopathic potential and other attributes can contribute to cultivar effects on weeds (Callaway, 1992; Olofsdotter *et al.*, 2002). The particular crop/weed combination may determine which attributes are most important. For example, in dryland and irrigated sweet maize production, *Panicum miliaceum* L. (Common Millet) fecundity was reduced more by a sweet maize cultivar that at anthesis had greater leaf area index, interception of photosynthetically active radiation and allocation of leaf area to the top of the canopy (Williams *et al.*, 2007). Barley varieties can be indexed for their suppressive ability against weeds based on just four varietal growth traits: reflectance, leaf area index, leaf angle and culm length (Hansen *et al.*, 2008). The authors suggest that indexing for competitiveness should become a standard practice in regular screening programmes of cereal varieties.

### **Objective 3: Prevent Undesirable Shifts in Weed Community Composition**

Weed communities are the consequence of environmental and management 'filters' acting on the local pool of species (Booth & Swanton, 2002). Because of their exceptionally high efficacy, herbicides result in overall low weed density and diversity; in some cases, the weed flora may be dominated by herbicide-resistant biotypes of a single species. Organic management, on the other hand, with a greater diversity of management tactics, can result in an overall increase in weed density, but also greater species diversity (Albrecht, 2005). In Albrecht's (2005) annual tracking of weed communities from 2 years before through 6 years after transition to organic management, species number increased initially but later declined. There was no change in species evenness, supporting the hypothesis that multiple stresses can encourage diversity while preventing dominance of one or a few pernicious species. Elsewhere, however, reduced-input management encouraged dominance of particular species (Squire *et al.*, 2000). Multiple-stress weed management systems composed of different suites of tactics can thus have markedly different filtering effects on weed communities. The community filtering properties of such systems appear to arise as an emergent property of the particular tactics comprising that system, with some systems having a greater scope for filtering activity (i.e. effects on a greater range of life-history processes affecting community assembly) than others. Cover cropping or use of a perennial forage crop, for example, can impose a great range of environmental and management stresses, possibly affecting weed seedling establishment, growth, reproduction and seed predation.

### Current Adoption and Challenges

Many successful farmers focus their weed management efforts exclusively on weed seedlings, through either herbicide application or cultivation. These 'critical weed-free period' managers reduce weed density early in the crop growth cycle and create an initial size advantage for the crop. 'Seedbank managers' follow an alternative philosophy for weed management. The latter group uses a systems perspective that relies on detailed knowledge of weed biology, especially emergence periodicity and reproductive phenology, to time and deploy disturbance events so as to maximise germination losses from the weed seedbank (increasing 'debits') and minimise weed seed rain into the seedbank (i.e. reducing 'credits'). These contrasting perspectives can be considered ends of a continuum of weed management philosophies. While there are likely more farmers toward the critical weed-free period management end of the spectrum, herbicide resistance in conventional agroecosystems and increasing weed densities and costs in organic systems are motivating many farmers to adopt a broader, more systemic perspective for weed management that includes a greater diversity of preventive and cultural practices targeting weeds at multiple 'choke points' in their life-cycles (Davis, 2006).

Simple combinations of weed management practices are easily tested using traditional experimental designs and statistical approaches (e.g. Melander & Rasmussen, 2001; Rasmussen, 2003). Increasing the number of practices to five or more is inherently challenging, both in the field and during subsequent analysis (e.g. Rasmussen *et al.*, 2014). Furthermore, the organising hypothesis of a multiple-stress approach to weed management is that individual stresses with relatively small effects, in combination, result in a cumulative effect that is large and measurable. Thus, significant effects of individual practices may rarely be of a magnitude greater than experimental or sampling error, and they must therefore be tested through simulation modelling (e.g. Westerman *et al.*, 2005) or cropping systems comparisons (e.g. Davis *et al.*, 2012).

### Cover Crops and Mulches

In this section we use the term 'cover crop' to indicate any non-cash-crop grown in the period between two cash crops and incorporated in the soil ('green manure'), and the term 'mulch' to indicate any living vegetation sown during the cash crop cycle ('living mulch') or plant biomass from a previous cash or cover crop left on soil as a surface cover ('dead mulch').

The scientific interest in cover crops and mulches dates back to the 1980s, when investigations showed the variety of agroecosystem benefits that can be expected from cover crops use. These include regulation of arthropod communities (Altieri & Schmidt, 1985), increased crop production in no-till systems (Wolf *et al.*, 1985; Bristow & Brun, 1987; Lemon *et al.*, 1990), soil erosion reduction (Barkusky, 1990; Langdale *et al.*, 1991), and improvement of soil physical conditions (Liebl *et al.*, 1992; Teasdale & Mohler, 1993) and of weed, insect pest and pathogen suppression (Smeda & Putnam, 1988; Phatak *et al.*, 1991; Schonbeck *et al.*, 1991; Teasdale *et al.*, 1991).

The typology of the cover crop/mulch system and its management largely determines the array of species traits associated with enhanced weed suppression. For example, in a living mulch system the cover crop should not be competitive with the main crop for



light, moisture and nutrients, and should therefore form a low but dense sward (den Hollander, 2012). If the cover crop is to be used as a dead mulch it would be advantageous if it yields as much biomass as possible, to prolong persistence of the weed suppression effect as long as possible after its destruction.

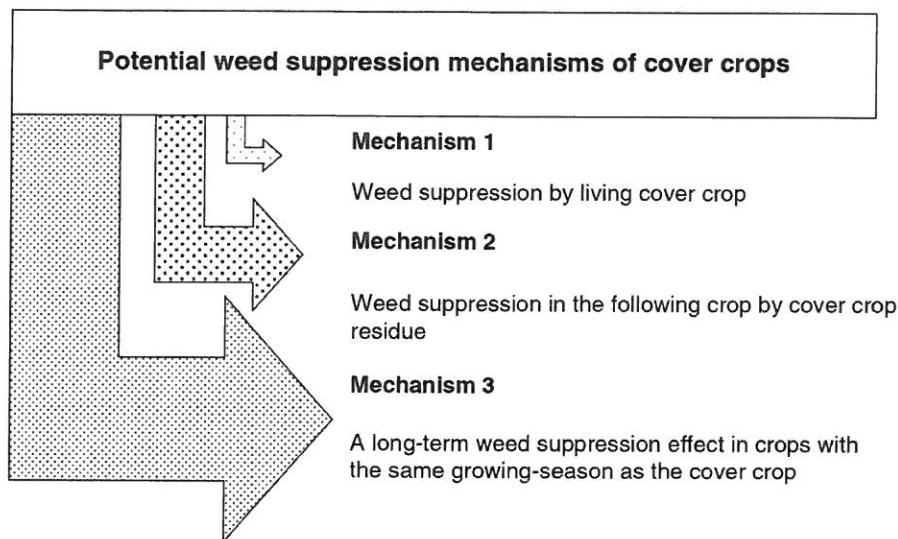
In the humid tropics, cover crops can be grown all year round. At northern latitudes, cover crops are mostly grown in the cold season (Lal *et al.*, 1991), except when they are used as a living mulch in summer crops (Teasdale *et al.*, 2007). In Mediterranean regions, both summer and winter species can be grown. However, winter species are preferred over summer species mainly due to the expected negative soil water balance by increased evapotranspiration, and the difficulty in matching the sowing time of a spring cash crop and living mulch with climatic conditions and with the need to minimise competition between the two species. The main winter cover crop is rye (*Secale cereale* L.), due to its voluminous biomass that impedes weed germination in the following cash crop (Teasdale *et al.*, 2007) and its ability to release allelochemicals (Moonen & Bàrberi, 2006) and reduce seedbank density in, for example, maize (Moonen & Bàrberi, 2004). Among legumes, hairy vetch (*Vicia villosa* Roth.) is a successful winter cover crop because it forms a dense sward suppressing winter weeds and improves soil fertility in the following cash crop (Mazzoncini *et al.*, 2011). When used as a mulch, it is also successful in suppressing weeds in the cash crop (Campiglia *et al.*, 2012).

Although the use of cover crops and mulches has become an almost standard practice in low-input and organic arable, vegetable and perennial cropping systems, there is no doubt that they can bring benefits to intensively managed systems as well. In the EU, this interest may even increase in view of the recent (1 January 2014) activation of the European Framework Directive on Sustainable Pesticide Use (EUR-Lex, 2009), which obliges all member states to adopt integrated pest management (IPM) practices in all cropping systems. Since weeds are among the greatest threats to crop yields, this development urges weed scientists to make the best possible use of all techniques available to control yield losses due to weeds, without neglecting the beneficial role they can have on the agroecosystem, for example their support to natural enemies of crop pests and pollinators (Bàrberi *et al.*, 2010; see also Gerowitt *et al.*, Chapter 5).

### Mechanisms of Cover Crop–Weed Interactions

As with all other weed management tactics, the use of cover crops and mulches should be part of a more complex strategy to reduce yield loss by weeds. The mode of action of cover crops and the resulting mulches is threefold and mainly based on physical and chemical modification of the soil environment in which weeds germinate and grow (Fig. 9.2).

- Cover crops can exert a direct weed suppression effect either as a pure crop or as a living mulch, whereas their residues act as a surface mulch or green manure (Fig. 9.2). The cover crops and living mulches exert a weed suppression capacity mainly through resource competition and, depending on the cover type, through volatilisation or leaching of allelochemicals from aerial parts of the plant or through root exudates (Chou, 1999) (mechanism 1).
- The mulch layer left on the soil surface or the residue incorporated in the soil after cover crop destruction results in changed soil physical conditions (Teasdale & Mohler, 1993) (mechanism 2), which are dependent on mulch type, quantity and structure



**Fig. 9.2** Potential cover crop–weed interaction mechanisms. *Source:* From Moonen (2004).

(Teasdale & Mohler, 2000). Surface mulches decrease diurnal temperature amplitude, reduce soil evaporation and hence result in a higher soil humidity, decreased radiation transmittance to the ground and modified radiation quality. Besides this, surface mulching can also result in leaching of allelochemicals or the release of these substances through mulch decomposition. Both factors influence weed seed germination and seedling early growth. However, the relative contribution of alteration of the physical environment and phytotoxicity to cover crop residue–weed interactions still has to be clarified. Optimally, cover crop residue should stimulate the cash crop to germinate and emerge, whereas it should impede weed germination and early development. However, it is not easy to plan this ahead because interactions depend on cover crop, crop and weed community composition, and soil conditions.

- A long-term weed suppression effect (mechanism 3) can be expected in those cash crops with a similar growing season as the cover crop, through depletion of the weed propagules surviving in the soil environment, if mechanism 1 explained above is successful (Teasdale *et al.*, 2007).

The efficacy of these mechanisms depends on the biological and ecological characteristics of the cover crops and mulches used, in combination with the dominant characteristics of the weed community and the following cash crop. Besides this, strong interactions exist with local pedo-climatic conditions. Recently, interest in such a trait-based approach has increased and Damour *et al.* (2014) have analysed cover crop traits useful for various agroecosystem functions, including weed control in banana systems, whereas Wilke and Snapp (2008) have done this for a winter cover crop in temperate North American climate zones.

### Challenges for Research

Since the 1980s, research on cover crops has advanced and interest in their application has been extended to all types of cropping systems. However, there are still some



technical, management and economic issues that impede successful large-scale cover crop utilisation. Renewed interest in IPM could be a great promoter of innovative research on cover crops. Issues that have found little attention so far are listed below.

- Although researchers have developed crop varieties adapted to almost all combinations of local pedo-climatic conditions worldwide, there has been little such work on cover crops, even though, if used correctly, they can be just as important as a good crop cultivar for obtaining a good crop yield or long-term economic benefits. Maul *et al.* (2011) showed that climatic factors of geographical origins of *Vicia villosa* accessions explained an important part of the genetic marker diversity and this information may help develop future breeding programmes.
- Currently, glyphosate is the most commonly used and successful method for terminating the growth of cover crops. However, this method cannot be applied in organic agriculture and may be reduced in other systems in the light of the present legislation on sustainable pesticide use and the rising number of glyphosate-resistant weed biotypes (see Moss, Chapter 7). Therefore, with the reduction or withdrawal of glyphosate use, we can identify a challenge to develop machinery aimed at terminating and incorporating or spreading cover crops and their mulches in an effective way, optimising their benefits for the cropping system (Mirsky *et al.*, 2013). This technical challenge will be particularly relevant in organic cropping systems based on reduced- or no-tillage. It must be stressed that, although promising, alternative production systems are unlikely to be adopted if adequate technical solutions are unavailable (Finckh, 2008; Lahmar, 2010).
- Provision of additional ecological services by cover crops, for example in relation to CO<sub>2</sub> sequestration.
- In order to convince farmers of the usefulness of increasing the complexity of their crop sequences by inserting cover crops or living mulches, it is necessary to quantify the presumed interactions between cover crops or mulches and other aspects of the cropping system, such as reduction of costs related to chemical weed control, variations in pathogen or pest attack to the crop and possible solutions, or increased levels of pollination or pest control due to beneficials that are attracted to cover crops.

These and similar questions framing the use of cover crops in innovative IPM/integrated crop management (ICM) systems designed upon sound agroecological principles are expected to become a priority in the years to come.

## Mechanical Weed Control

Mechanical weed control destroys weeds or reduces their competitive ability by physical means. In this chapter, emphasis is on tillage, but also no-till methods exist, for example mowing and cutting (see Hatcher, Chapter 13). Mechanical weed control is mainly used in organic agriculture, but row cultivation still plays a role in conventional agriculture, where it has been used since the eighteenth century.

Various forms of tillage are used for mechanical weed control, but cultivating tillage, previously referred to as tertiary tillage, is the key component in mechanical control in growing crops. Cultivating tillage is shallow tillage in early crop growth stages with the aim to destroy weed seedlings. Besides weed control, it may also loosen the soil and

**Table 9.1** Different principles of mechanical weed control defined relative to tillage depth, orientation and timing.

Tillage depth	Tillage orientation relative to crop rows	Timing relative to the presence of crops	
		Crops present	Crops absent
Shallow (0–5 cm)	Full-field	Full-field cultivation	
	Between rows	Inter-row cultivation (hoeing)	
	In rows	Intra-row cultivation	
Deep (>5 cm)	Full-field		Stubble cultivation and other deep cultivation against perennial weeds

improve tilth, which occasionally is more important to crop yield than the weed control itself (Brandsætter *et al.*, 2012).

All forms of tillage have impacts on weeds, but only tillage that is targeted against weeds is considered as mechanical weed control. Thus, mouldboard ploughing is not considered as direct mechanical weed control unless it is purposely targeted against perennial weeds. Nevertheless, ploughing is extremely important in preventing weeds due to burial of seeds and vegetative propagules and it is doubtful whether non-inversion tillage is possible in organic agriculture under European conditions (Mäder & Berner, 2012; Melander *et al.*, 2013). Non-inversion tillage is heavily dependent on glyphosate products, and even in organic cropping systems with mouldboard ploughing perennial weeds may be challenging to manage (Rasmussen *et al.*, 2014). Different principles of mechanical weed control are defined by tillage depth, orientation and timing (Table 9.1). The criteria give rise to different patterns of soil disturbances, which are important because plant response to tillage depends on the interaction between pattern of soil disturbance and the growth characteristics of the plant. The diversity of machinery used for mechanical weed control is large (Bowman, 1997; Van der Schans *et al.*, 2006; Cloutier *et al.*, 2007), but there are similarities among implements and soil disturbance patterns within each approach for mechanical weed control (Table 9.1). In Europe, the most common implements for weed control in growing crops are spring-tine harrows, inter-row cultivators and intra-row cultivators. Spring-tine harrows are used for full-field cultivation, inter-row cultivators are for cultivation between crop rows and intra-row cultivators are for weeds within crop rows. Inter- and intra-row cultivators are mainly used in row crops with wide distances between rows (e.g. maize and vegetables) and spring-tine harrows are mainly used in crops with narrow row distances (e.g. cereals). However, spring-tine harrows are also used before crop emergence in row crops and after crop emergence, if crop plants are significantly more resistant to soil disturbance than weeds (high selectivity). Harrows have higher capacity (speed and working width) than intra-row cultivators.

In general, spring-tine harrows have not been modernised significantly in recent years, but there are ongoing improvements of the adjustment of tine angle and cultivation depth, which makes modern harrows more user-friendly than older ones. Recently, there have been developed PTO-powered harrows (Agrotechniek Holland BV) with tine



sections that move back and forth perpendicular to the driving direction. This is useful to avoid clogging of the machinery with crop residues after non-inversion tillage.

Inter-row cultivators often have goosefoot sweeps (hoes) that are dragged through the soil, but PTO-driven brushes and rotary tillers are also used for inter-row cultivating. Recent modernisation has been through automatic guidance systems that steer implements precisely along the crop rows (Van der Weide *et al.*, 2008).

Intra-row cultivators are relatively new implements which cultivate the soil close to or within crop rows. There exist various low-tech implements such as torsion and finger-weeders (Fig. 9.3) (Bowman, 1997; Van der Schans *et al.*, 2006), and in recent years, high-tech implements have been developed and commercialised (Fig. 9.4) (Tillett *et al.*, 2008; Van der Weide *et al.*, 2008). These high-tech implements mainly use machine

**Fig. 9.3** Intra- and inter-row weed control in maize. Finger-weeders control weeds within crop rows and sweeps control weeds between rows. (See insert for colour representation of the figure.)



**Fig. 9.4** Intra-row cultivation with cultivation blades that are moved in and out of the rows based on machine vision guidance. (See insert for colour representation of the figure.)

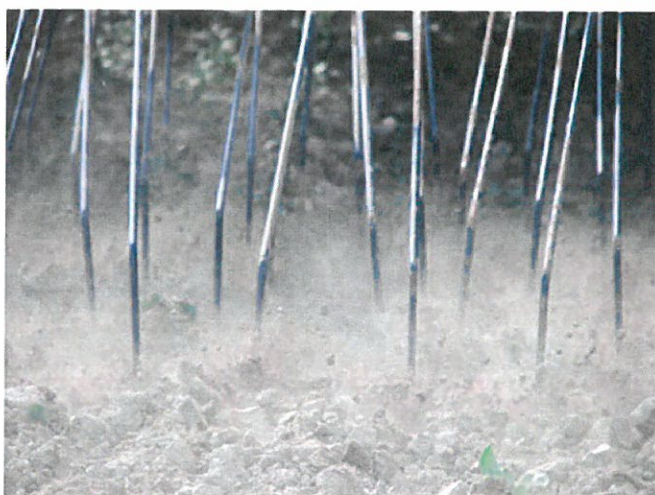
vision for the precision guidance of cultivation blades that cultivate between crop plants in the rows.

Tine- or disc-based implements are common in stubble cultivation against perennial weeds, but rotating implements driven by the PTO are also used. A common mechanical strategy against perennial weeds consists of repeated cultivations ending with mouldboard ploughing to exhaust reserves within vegetative propagules (Melander *et al.*, 2012). Stubble cultivation has little or no effect on most seed-propagated weed species (Pekrun & Claupein, 2006).

### How It Works

Different implements move the soil in different ways and therefore have different effects on weeds. Cultivation tillage works mainly through soil burial and uprooting of weed seedlings, and it has little or no effect on perennial weeds that propagate vegetatively (Melander *et al.*, 2005). Tine cultivators do not kill weeds by themselves but by the soil disturbance they generate (Fig. 9.5). Kolb and Gallandt (2012) noted that uprooting is the primary mechanism causing weed mortality, whereas Jensen *et al.* (2004) reasoned that soil burial is the main action if plants are strongly anchored. Both reports acknowledged Kurstjens and Kropff's (2001) findings that uprooting is important when plants are weakly anchored. The tricky question is, however, whether weeds are strongly or weakly anchored. A recent study indicated that the main action of tine cultivators is soil covering in crops where both crop and weeds emerge simultaneously (Rasmussen *et al.*, 2012). Inter-row cultivators with goosefoot sweeps or rotary tillers also have a cutting action and uproot more plants than tine cultivators.

Cultivation tillage can take place before crop emergence when weeds are in the 'white thread' stage (referring to the appearance of the germinating but not emerged weed seedlings). Pre-emergence cultivation influences weeds in a rather unpredictable way due to a trade-off between mortality and stimulation of germination. Hence, cultivation not only destroys weeds, it may also initiate new flushes of weeds (Brandsætter *et al.*,



**Fig. 9.5** Full-field cultivation with a spring-tine harrow with long flexible tines. Soil disturbance constitutes the main action against weeds and not the tines themselves. (See insert for colour representation of the figure.)



2012). Intra-row cultivators can have cutting actions, when hoes are steered in and out of the crop rows, or uprooting and covering actions in case of torsion weeders and finger-weeders.

Mechanical control of perennial weeds is mainly based on deep and repeated post-harvest cultivations and the mechanisms are uprooting, desiccation, dismemberment and burial of vegetative propagules. In recent years, there has been increasing interest in new machinery for uprooting and destroying below-ground vegetative propagules by crushing (Melander *et al.*, 2011). This method, however, is only feasible against weeds with large proportions of roots or rhizomes in the plough layer, such as *Elytrigia repens* Desv. ex Nevski (common Couch).

### Shortcomings

In general, mechanical weed control cannot compete with herbicides in terms of efficacy and cannot act as a stand-alone method: it has to be supplemented by preventive and cultural methods or low doses of herbicides. However, in some crops (e.g. lettuce), experiments have shown that the stale seedbed technique in combination with mechanical control of emerging weeds can reduce the weed population during crop growth as effectively as chemical control (Riemens *et al.*, 2007).

Low weed control effects are due to three main reasons: lack of residual effects; low selectivity; and lack of knowledge about optimal intensity and timing of cultivation.

The lack of residual effects is relevant for both cultivating tillage and stubble cultivation against perennial weeds. The longer the time between cultivation and weed assessment, the lower the effects that are recorded, due to new weed emergence and/or recovery (Rasmussen *et al.*, 2010).

Low selectivity between crop and weeds is a major limitation for full-field and intra-row cultivation. Both cultivation approaches may be associated with significant crop damage, because weed control and crop damage are strongly correlated (Rasmussen *et al.*, 2010, 2012). Large crop plants and small weeds are crucial for high selectivity and successful weed control (Fig. 9.6). This is even the case with intelligent intra-row weeders, because the vision systems only work properly when crop plants are significantly larger than the weeds. Therefore, current high-tech cultivators only work in transplanted crops and not in direct-sown crops. Nonetheless, recent research suggests that improvements are possible (Hemming *et al.*, 2011). It is possible to guide tillage implements in directly sown crops by use of mapping techniques that use real-time kinematic global positioning system (RTK-GPS) (high precision) to give accurate information about the position of individual crop plants, but this technology has not been developed for practical use yet (Rasmussen *et al.*, 2012).

Methods to optimise the cultivation intensity of mechanical weed control with low selectivity need elaboration and comprehensive experimental work, as outlined in Rasmussen *et al.* (2010) and Rueda-Ayala *et al.* (2011), whereas inter-row cultivation controls weeds almost completely under favourable conditions and there are only minor problems with selectivity (Melander *et al.*, 2005). Post-harvest cultivation is not limited by selectivity but by unwanted side-effects on crops, but repeated cultivations in autumn are a threat to soil conservation and nutrient leaching because they leave the soil bare for long periods.





**Fig. 9.6** Large crop plants and small weeds are crucial for a high selectivity with full-field cultivations. In the bottom picture, weeds are small relative to the crop and efficient mechanical weed control is possible with minor crop damage (high selectivity). In the top picture, there is a large weed plant (*Sinapis arvensis*), which is not possible to control without significant crop damage (low selectivity). (See insert for colour representation of the figure.)

### Challenges for Research

Research in mechanical weed control includes interactions between soil, machinery, weeds and crops, and it produces partial data, because research cannot handle all interactions within a single experiment.

Research covers a wide range of disciplines and approaches. Some scientists draw their knowledge from farmers' practices and test the effectiveness of mechanical weed control in different environments (Van der Schans *et al.*, 2006; Van der Weide *et al.*, 2008). Others develop new implements (Tillett *et al.*, 2008), test and compare implements (Rasmussen *et al.*, 2012), develop new experimental approaches and models to predict the optimum tillage intensity (Rueda-Ayala *et al.*, 2011), improve basic

knowledge on plant responses to soil disturbance (Kurstjens & Kropff, 2001), and quantify interactions between different types of mechanical weed control (Brandsæter *et al.*, 2012), different types of physical weed control (Rasmussen *et al.*, 2012) or different types of weed management (Melander *et al.*, 2005). Within each topic there are several research and development needs. Van der Weide *et al.* (2007) summarised a range of development needs in row crops and Vanhala *et al.* (2004) gave detailed recommendations on topics and methodologies within mechanical weed control.

Research needs expressed by farmers are influenced by their farming style. Riemens *et al.* (2010) showed that crop growth-oriented farmers accepted fewer weeds than market-oriented farmers, and that some farmers believe that soil structural damage occurs when weeds are mechanically controlled and thus do not often control weeds mechanically. To further improve mechanical weed control, different stakeholder perspectives must have effective linkages because research in mechanical weed control is complex and limited by sparse funding. The low-hanging fruits have been harvested, and if research is to contribute significantly to further improvements, coordination and strategic research agendas are needed. The EU is aiming to promote low herbicide-input weed management, giving priority to non-chemical methods, but the needed research stimulation and funding is lagging behind.

It would be valuable if future research, besides further improvement of machinery and the possibilities to use them, supports the development of model-based decision support systems, which include decisions about timing, frequency and intensity of mechanical weed control treatments. Occasionally, mechanical weed control is associated with negative site-effects such as crop and soil damages, which demand that the positive and negative effects of mechanical weed control are evaluated together. This requires better quantitative knowledge about trade-offs. Mechanical weed control should only take place when the positive effects dominate the negative, and timing and intensity should be optimised according to the actual weed infestation and its importance for the crop. Based on quantitative studies of the interactions between timing and intensity of weed harrowing (Rasmussen *et al.*, 2010; Rueda-Ayala *et al.*, 2011), Rueda-Ayala *et al.* (2013) made a first attempt to suggest a rule-based decision support system to adjust the intensity of weed harrowing in winter cereals. Whether this approach will guide future research and improve weed harrowing practice in the future is still too early to evaluate, but it is thought-provoking that weed research has refrained from developing decision support systems within mechanical weed control for so many years.

## Thermal Weed Control

Thermal weed control is obtained when thermal energy is transferred to plant material (leaves, stems, flowers, propagules, etc.) in a manner that causes the plant structures to denature and eventually die. Thermal energy can be applied through either freezing or heating, but, at present, only heating has had significant deployment. The heat causes denaturation and aggregation of cellular proteins and protoplast expansion and rupture (Ellwanger *et al.*, 1973). Detrimental effects on plant tissue usually occur when temperature rises above 45 °C. The sensitivity of weed plants to heating strongly depends on different factors such as target plant structure (e.g. below-ground propagules or

**Table 9.2** Average number of rhizome buds of *Elytrigia repens* sprouting after treatment with hot water at four different temperatures and durations. Source: From Melander *et al.* (2011).

Temperature (°C)	Time (seconds)	Number of sprouted buds
20 (unheated)		40.0
50	30	32.3
	60	39.3
	300	30.5
	600	12.8
60	5	39.8
	30	4.0
	60	2.3
	300	0.0
70	5	0.3
	30	0.0
	60	0.0
	300	0.0
90	5	0.0
	15	0.0
	30	0.0
	60	0.0

above-ground vegetation), plant species, water status of the plant, weather conditions and exposure time (Levitt, 1980).

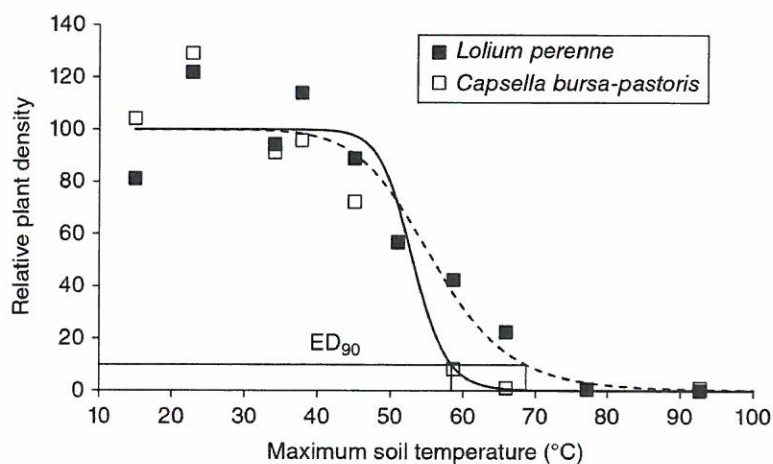
However, despite the influence of multiple factors on the outcome of heating, temperature and exposure time are most important for the adjustment of thermal weed control effects (Table 9.2). Low temperatures (below approx. 55°C) require longer duration (from hours to days) to provide sufficient weed control effects, while higher temperatures can be effective within seconds. Both generative and vegetative propagules of most weed species are killed within a temperature range of 60 to 80°C irrespective of the heating source. However, thermal conductivity and maximum temperature determine the duration needed to reach mortality (Melander & Jørgensen, 2005). Thermal conductivity is higher with water than with gasses (air and propane flames), and lethal heat penetration into plant tissue is easier with water-based heating sources such as steam and hot water than with flames or hot air.

Heat for weed control purposes can be applied by steam (Bårberi *et al.*, 2009), hot water (Fig. 9.7) (Hansson & Ascard, 2002), hot air, flames (Ascard, 1995), infrared and ultraviolet (UV) radiation (Andreasen *et al.*, 1999), lasers (Heisel *et al.*, 2001), microwaves (Sartorato *et al.*, 2006), electrocution, freezing or solarisation (Linke, 1994). Heating intensity and its effect on plant growth can be described by sigmoid dose-response functions similar to the ones used in herbicide studies (Streibig *et al.*, 1993; see Kudsk, Chapter 6). Heating intensity is expressed as the energy applied (Ascard, 1995;





**Fig. 9.7** Thermal weed control on a cycle track using hot water applied with foam to promote heat duration. (See insert for colour representation of the figure.)



**Fig. 9.8** Soil steaming effects on the relative number of *Lolium perenne* L. (Perennial Rye-grass) and *Capsella bursa-pastoris* (L.) Medik (Shepherd's purse) seedlings in a laboratory study. *Capsella bursa-pastoris* seeds occurred naturally in the soil samples prior to steaming, while dry seeds of *L. perenne* were added. Horizontal and vertical lines show  $ED_{90} = 58.4^{\circ}\text{C}$  for *C. bursa-pastoris* and  $ED_{90} = 68.7^{\circ}\text{C}$  for *L. perenne*. Source: Modified from Melander and Jørgensen (2005).

Sartorato *et al.*, 2006) or the measured temperature (Fig. 9.8). These functions can be used to calculate the energy or temperature needed to attain a certain weed control level, often denoted as  $ED_{50}$  or  $ED_{90}$  values corresponding to 50% and 90% weed control, respectively (Fig. 9.8). High weed control levels can be very energy-demanding to achieve because the sigmoidal curve declines exponentially when passing the point of inflection.

Thermal weed control can be applied either above or below ground depending on the weed problem. For the control of above-ground vegetation, the heat requirement depends on the weed species, their growth stages, their water status and the presence of moisture on the leaf surface. For example, flaming weed plants at 4 to 12 leaves requires two- to four-fold higher rates for control than those at the 0- to 4-leaf stage (Ascard, 1995). Grass-weeds are more difficult to control thermally than most broadleaf species due to grasses having protected growing points. Other factors affecting heat tolerance are lignification and protective layers of hair and wax that may reduce heat transmission. Wet leaves require more energy to heat than drier leaves, and this is attributed to energy absorption by water. Below-ground plant material also responds differently to heating, with morphology and moisture content of propagules being the most important biological factors governing heating effectiveness (Fig. 9.8). Dry and large seeds with hard and low-permeable seed coats are considered most resistant to heating (Melander & Jørgensen, 2005).

Although water-based heating sources provide higher thermal conductivity, they are more energy demanding than, for example, flaming. While broadcast flaming against weed seedlings requires about  $2300 \text{ MJ ha}^{-1}$  (corresponding to approx.  $50 \text{ kg propane gas ha}^{-1}$ ), the same weed control treatment with hot water would use roughly twice as much energy. UV-radiation, lasers and microwaves are even more energy demanding than flame weeding, requiring 4, 10 and 40 times more energy for equivalent weed control, respectively. However, the application technology for these heating techniques still needs further development to become feasible for weed control. Solarisation is the only thermal method that does not utilise fossil energy to produce heat, apart from the production of plastic sheets and application in practice.

### Thermal Weed Control in Practice

Flaming, hot water and steam are the primary heat sources for weed control purposes in practice. The main areas of application are horticultural crops, glasshouses and hard surfaces in amenity areas. Flaming is the most commonly used thermal method in organic field horticultural crops, predominantly applied as a pre-crop-emergence treatment to control early emerged weed seedlings in slowly germinating vegetable crops (Melander *et al.*, 2005; see Tei & Pannacci, Chapter 12). So far, no thermal methods have demonstrated any potential for use in agricultural crops such as cereals, pulses and oilseed rape. In maize, however, weed-effective propane gas dosages can be used for broadcast flaming at the 5-leaf growth stage with an acceptable impact on the crop (Ulloa *et al.*, 2011).

Below-ground propagules (seeds and vegetative fragments) and to some extent protected growing points above ground remain unaffected when applying the heat from above the ground, usually resulting in renewed weed growth with the need for subsequent treatments. Only soil steaming and solarisation, where a targeted soil volume is heated, can provide longer lasting control (Linke, 1994; Melander & Kristensen, 2011). Recolonisation only occurs when new propagules enter from outside the treated zone. Mobile soil steaming is commercially used on raised beds in short-term field salad crops which have a strong need to control soil-borne pathogens. Band steaming is a new technology that only heats a limited soil volume of the intra-row area of row crops, enough to control weed seedlings that would otherwise emerge in the rows. The energy

consumption is approximately six times lower than for mobile soil steaming on raised beds (Melander & Kristensen, 2011). Soil solarisation is based on utilising solar energy for heating soil mulched with transparent polyethylene (PE), reaching temperatures of 40 to 55 °C in the upper soil layer (Linke, 1994). Chapter 12 by Tei and Pannacci further explains the practical application of thermal methods in field vegetables.

### Challenges for Research

In addition to high energy demand, thermal methods have low work rates and relatively high purchase costs, may require multiple treatments for satisfactory control and, in the case of flaming, may cause fires under certain circumstances. Thermal weed control has very little application in conventional field crops because herbicides are selective, less costly and easier to apply. The use of thermal weeding in amenity areas is mainly decided by national or local policies driven by public concerns about pesticide use (Kristoffersen *et al.*, 2008). Organic farming utilises thermal weed control whenever relevant, provided that the national guidelines allow the method considered, for example the allowance for using broadcast steaming varies among European countries. Despite the agronomic relevance of thermal methods for weed control, the technology is still controversial in organic farming in view of potential climate change and the desirability of reducing greenhouse gas emissions. Future research therefore needs to address the issues mentioned below, if thermal weed control should have a place in the future.

- Application technologies need innovation to minimise heat loss from the equipment itself and to target the heat more precisely. For example, selective flaming in row crops could be assisted by vision technology to detect crop plants to limit the treatment to the weedy intra-row area only while avoiding injuring the crop.
- Strategies for combining thermal treatments with other weed control methods should be explored more extensively in order to reduce energy inputs; mechanical interventions may replace thermal methods for inter-row weed control in row crops.
- The energy source for thermal methods should be changed from fossil energy to bio-fuels whenever possible.
- A better understanding of heat transmission from the applicator to the plant as well as heat transmission inside the plant would help reduce energy consumption and improve weeding effectiveness.

Research is not the only important contributor to improve thermal weed control; the industry also needs to play a stronger role. Currently, manufacturers of thermal implements are very small enterprises with limited financial capacity; future policies on pesticide use, such as the IPM directive launched from the EU (Directive 2009/128/EC) may motivate stronger investments into the sector.

### Conclusion

Non-chemical weed management is mainly adopted in organic crop production, as conventional growers still perceive it as more costly and less reliable than herbicide-based weed control programmes. Still, we believe that research has added considerable knowledge and understanding of the features of non-chemical weed control methods in



row crops and small grain cereals that may benefit conventional growers in a future with increasing uncertainties about herbicide use. Improvements are needed though to lower costs, increase reliability in terms of weeding effectiveness and crop tolerance, and improve operational efficiency. New techniques and ideas are regularly emerging and advanced technologies may have the potential to radically improve the methods and probably also make them relevant for wider usage in conventional cropping. Innovations made within the electronics and information technology sectors keep emerging with amazing speed and will likely add many new options for guiding and improving accuracy of physical weeding devices.

It is expected that non-chemical management options gradually will become more important components in future weed control programmes in conventional crop production. Problems with herbicide resistance and new pesticide regulations create stronger incentives for growers to limit herbicide applications. Pesticide action plans have been launched in several European countries, all asking for a reduction in herbicide use. On top of this, the EU has recently passed a directive that imposes on each member state the initiation of measures that will push crop protection towards IPM solutions (Melander *et al.*, 2013). Thus, we foresee a greater immediate usage of preventive and cultural methods to supplement herbicide use. Current crop compositions and the sequence in which they are grown in European agriculture need special reconsideration because they are entirely driven by economic motives and not the desire to prevent the proliferation of detrimental weed problems. EU and national subsidy programmes promoting more varied crop sequencing can help broaden the crop spectrum and still maintain farm revenues. Catch cropping is now mandatory in some European countries, for example France and Denmark, to prevent nutrient losses through leaching; it can add diversity to the system and thereby mitigate specific weed problems. Other cultural tactics aimed at strengthening crop growth and suppressive ability against weeds may contribute to limiting the need for herbicides. Advanced direct physical methods may substitute or even replace herbicides, depending on the innovations made and whether pesticide policies continue to push agriculture towards alternatives.

## References

- Albrecht H (2005) Development of arable weed seedbanks during the 6 years after the change from conventional to organic farming. *Weed Research* **45**, 339–350.
- Altieri MA & Schmidt LL (1985) Cover crop manipulation in northern California orchards and vineyards – effects on arthropod communities. *Biological Agriculture & Horticulture* **3**, 1–24.
- Anderson RL (2003) An ecological approach to strengthen weed management in the semiarid Great Plains. *Advances in Agronomy* **80**, 33–62.
- Andersson TN & Milberg P (1996) Weed performance in crop rotations with and without leys and at different nitrogen levels. *Annals of Applied Biology* **128**, 505–518.
- Andersson TN & Milberg P (1998) Weed flora and the relative importance of site, crop, crop rotation, and nitrogen. *Weed Science* **46**, 30–38.
- Andreasen C, Hansen L & Streibig JC (1999) The effect of ultraviolet radiation on the fresh weight of some crops and weeds. *Weed Technology* **13**, 554–560.

- Ascard J (1995) Effects of flame weeding on weed species at different developmental stages. *Weed Research* **35**, 397–411.
- Bàrberi P, Moonen AC, Peruzzi A, Fontanelli M & Raffaelli M (2009) Weed suppression by soil steaming in combination with activating compounds. *Weed Research* **49**, 55–66.
- Bàrberi P, Burgio G, Dinelli G *et al.* (2010) Functional biodiversity in the agricultural landscape: relationships between weeds and arthropod fauna. *Weed Research* **50**, 388–401.
- Barkusky D (1990) Water erosion control by no-plowing tillage silage maize growing in the north of the GDR. *Archiv für Acker und Pflanzenbau und Bodenkunde – Archives of Agronomy and Soil Science* **34**, 375–384.
- Baumann DT, Kropff MJ & Bastiaans L (2000) Intercropping leeks to suppress weeds. *Weed Research* **40**, 359–374.
- Benvenuti S, Macchia M & Miele S (2001) Quantitative analysis of emergence of seedlings from buried weed seeds with increasing depth. *Weed Science* **49**, 528–535.
- Booth BD & Swanton CJ (2002) Assembly theory applied to weed communities. *Weed Science* **50**, 2–13.
- Bowman G (1997) *Steel in the Field: A Farmer's Guide to Weed Management Tools*. Sustainable Agricultural Publications, University of Vermont, Burlington.
- Brandsætter LO, Mangerud K & Rasmussen J (2012) Interactions between pre- and post-emergence weed harrowing in spring cereals. *Weed Research* **52**, 338–347.
- Bristow PR & Brun CA (1987) Effect of soil compaction and perennial cover crop on production in red raspberry. *Hortscience* **22**, 1096–1096.
- Callaway MB (1992) A compendium of crop varietal tolerance to weeds. *American Journal of Alternative Agriculture* **7**, 169–180.
- Campiglia E, Radicetti E & Mancinelli R (2012) Weed control strategies and yield response in a pepper crop (*Capsicum annuum* L.) mulched with hairy vetch (*Vicia villosa* Roth.) and oat (*Avena sativa* L.) residues. *Crop Protection* **33**, 65–73.
- Chou CH (1999) Roles of allelopathy in plant biodiversity and sustainable agriculture. *Critical Reviews in Plant Sciences* **18**, 609–636.
- Christensen S (1994) Weed suppression ability of spring barley varieties. *Weed Research* **35**, 241–247.
- Cloutier DC, van der Weide RY, Peruzzi A & Leblanc M (2007) Mechanical weed management. In: *Non-Chemical Weed Management: Principles, Concepts and Technology* (eds MK Upadhyaya & RE Blackshaw), 111–134. CABI, Wallingford.
- Damour G, Dorel M, Quoc HT, Meynard C & Risède JM (2014) A trait-based characterization of cover plants to assess their potential to provide a set of ecological services in banana cropping systems. *European Journal of Agronomy* **52**, 218–228.
- Davis AS (2006) When does it make sense to target the weed seed bank? *Weed Science* **54**, 558–565.
- Davis AS & Liebman M (2003) Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. Green manure and tillage timing. *Weed Science* **51**, 919–929.
- Davis AS & Raghu S (2010) Weighing abiotic and biotic influences on weed seed predation. *Weed Research* **50**, 402–412.
- Davis AS, Hill JD, Chase CA, Johanns AM & Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS ONE* **7**(10), e47149.

- den Hollander NG (2012) *Growth characteristics of several clover species and their suitability for weed suppression in a mixed cropping design*. PhD thesis, Wageningen University, Wageningen.
- Ellwanger TC Jr, Bingham SW, Chappell WE & Tolin SA (1973) Cytological effects of ultra-high temperatures on maize. *Weed Science* **21**, 299–303.
- Eur-LEX (2009) *Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides (Text with EEA relevance)*. Official Journal of the European Union, OJ L 309, 24 November.
- Finckh MR (2008) Integration of breeding and technology into diversification strategies for disease control in modern agriculture. *European Journal of Plant Pathology* **120**, 399–409.
- Gallandt ER (2004) Soil-improving practices for ecological weed management. In: *Weed Biology and Management* (ed. Inderjit), 267–284. Kluwer Academic Publishers, Dordrecht.
- Gallandt ER, Liebman M, Corson S, Porter GA & Ullrich SD (1998) Effects of pest and soil management systems on weed dynamics in potato. *Weed Science* **46**, 238–248.
- Gallandt ER, Molloy T, Lynch RP & Drummond FA (2005) Effect of cover-cropping on invertebrates. *Weed Science* **53**, 69–76.
- Hansen PK, Kristensen K & Willas J (2008) A weed suppressive index for spring barley (*Hordeum vulgare*) varieties. *Weed Research* **48**, 225–236.
- Hansson D & Ascard J (2002) Influence of developmental stage and time of assessment on hot water weed control. *Weed Research* **42**, 307–316.
- Heggenstaller AH, Menalled FD, Liebman M & Westerman PR (2006) Seasonal patterns in post-dispersal seed predation of *Abutilon theophrasti* and *Setaria faberi* in three cropping systems. *Journal of Applied Ecology* **43**, 999–1010.
- Heisel T, Schou J, Christensen S & Andreassen C (2001) Cutting weeds with a CO<sub>2</sub> laser. *Weed Research* **41**, 19–30.
- Hemming J, Nieuwenhuizen AT & Struik LE (2011) Image analysis system to determine crop row and plant positions for an intra-row weeding machine. *Proceedings of the CIGR International Symposium on Sustainable Bioproduction*, 19–23 September, Tokyo, 1–7.
- Jensen PK (2009) Longevity of seeds of four annual grasses and two dicotyledon weed species as related to placement in the soil and straw disposal technique. *Weed Research* **49**, 592–601.
- Jensen RK, Rasmussen J & Melander B (2004) Selectivity of weed harrowing in lupin. *Weed Research* **44**, 245–253.
- Kolb LN & Gallandt ER (2012) Weed management in organic cereals: advances and opportunities. *Organic Agriculture* **2**, 23–42.
- Kolb LN, Gallandt ER & Mallory EB (2012) Impact of spring wheat planting density, row spacing, and mechanical weed control on yield, grain protein, and economic return in Maine. *Weed Science* **60**, 244–253.
- Kristoffersen P, Rask AM, Grundy AC *et al.* (2008) A review of pesticide policies and regulations for urban amenity areas in seven European countries. *Weed Research* **48**, 201–214.
- Kurstjens DAG & Kropff MJ (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research* **41**, 211–228.



- Lahmar R (2010) Adoption of conservation agriculture in Europe; lessons of the KASSA project. *Land Use Policy* 27, 4–10.
- Lal R, Regnier E, Eckert DJ, Edwards WM & Hammond R (1991) Expectations of cover crops for sustainable agriculture. In: *Cover Crops for Clean Water* (ed. WL Hargrove), 1–11. Soil and Water Conservation Society, Ankeny, Iowa.
- Langdale GW, Blevins RL, Karlen DL *et al.* (1991) Cover crop effects in soil erosion by wind and water. In: *Cover Crops for Clean Water* (ed. WL Hargrove), 15–22. Soil and Water Conservation Society, Ankeny, Iowa.
- Lemerle D, Verbeek B, Cousens RD & Coombes NE (1996) The potential for selecting wheat varieties strongly competitive against weeds. *Weed Research* 36, 505–513.
- Lemon RG, Hons FM & Saladino VA (1990) Tillage and clover cover crop effects on grain-sorghum yield and nitrogen uptake. *Journal of Soil and Water Conservation* 45, 125–127.
- Levitt J (1980) *Responses of Plants to Environmental Stresses. Vol. I: Chilling, Freezing and High Temperature Stresses*, 2nd edn. Academic Press, New York.
- Liebl R, Simmons FW, Wax LM & Stoller EW (1992) Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). *Weed Technology* 6, 838–846.
- Liebman M & Gallandt ER (1997) Many little hammers: ecological approaches for management of crop–weed interactions. In: *Ecology in Agriculture* (ed. LE Jackson), 291–343. Academic Press, San Diego.
- Liebman M, Menalled FD, Buhler DD *et al.* (2004) Impacts of composted swine manure on weed and maize nutrient uptake, growth, and seed production. *Weed Science* 52, 365–375.
- Linke KH (1994) Effects of soil solarization on arable weeds under Mediterranean conditions: control, lack of response or stimulation. *Crop Protection* 13, 115–120.
- Mäder P & Berner A (2012) Development of reduced tillage systems in organic farming in Europe. *Renewable Agriculture and Food Systems* 27, 7–11.
- Maul J, Mirsky S, Emche S & Devine T (2011) Evaluating a germplasm collection of the cover crop hairy vetch for use in sustainable farming systems. *Crop Science* 51, 2615–2625.
- Mazzoncini M, Sapkota TB, Bàrberi P, Antichi D & Risaliti R (2011) Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. *Soil & Tillage Research* 114, 165–174.
- Melander B & Jørgensen MH (2005) Soil steaming to reduce intra-row weed seedling emergence. *Weed Research* 45, 202–211.
- Melander B & Kristensen JK (2011) Soil steaming effects on weed seedling emergence under the influence of soil type, soil moisture, soil structure and heat duration. *Annals of Applied Biology* 158, 194–203.
- Melander B & Rasmussen G (2001) Effects of cultural methods and physical weed control on intrarow weed numbers, manual weeding and marketable yield in direct-sown leek and bulb onion. *Weed Research* 41, 491–508.
- Melander B, Rasmussen IA & Bàrberi P (2005) Integrating physical and cultural methods of weed control – examples from European research. *Weed Science* 53, 369–381.
- Melander B, Holst N, Jensen PK, Hansen EM & Olesen JE (2008) *Apera spica-venti* population dynamics and impact on crop yield as affected by tillage, crop rotation, location and herbicide programmes. *Weed Research* 48, 48–57.

- Melander B, Mathiassen SK, Nørremark M, Kristensen EF, Kristensen JK & Kristensen K (2011) Physical destruction of the sprouting ability of *Elytrigia repens* rhizome buds. *Weed Research* **51**, 469–477.
- Melander B, Holst N, Rasmussen IA & Hansen PK (2012) Direct control of perennial weeds between crops – implications for organic farming. *Crop Protection* **40**, 36–42.
- Melander B, Munier-Jolain N, Charles R *et al.* (2013) European perspectives on the adoption of non-chemical weed management in reduced tillage systems for arable crops. *Weed Technology* **27**, 231–240.
- Melander B, Lattanzi B & Pannacci E (2015) Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. *Crop Protection* **72**, 1–8.
- Menalled FD, Liebman M & Buhler DD (2004) Impact of composted swine manure and tillage on common waterhemp (*Amaranthus rudis*) competition with soybean. *Weed Science* **52**, 605–613.
- Menalled FD, Liebman M & Renner K (2006) The ecology of weed seed predation in herbaceous crop systems. In: *Handbook of Sustainable Weed Management* (eds HP Singh, DR Batish & RK Kohli), 297–327. Food Products Press, Binghamton, New York.
- Mirsky SB, Ryan MR, Teasdale JR *et al.* (2013) Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern United States. *Weed Technology* **27**, 193–203.
- Mohler CL (2001a) Mechanical management of weeds. In: *Ecological Management of Agricultural Weeds* (eds M Liebman, CL Mohler & CP Staver), 139–209. Cambridge University Press, Cambridge.
- Mohler CL (2001b) Enhancing the competitive ability of crops. In: *Ecological Management of Agricultural Weeds* (eds M Liebman, CL Mohler & CP Staver), 269–321. Cambridge University Press, Cambridge.
- Moonen AC (2004) *A system-approach to study the weed suppression capacity of autumn-sown cover crops in a biennial rotation of maize and durum wheat*. PhD thesis. Agricoltura Eco-compatibile e Qualità degli Alimenti, Università di Pisa, Pisa.
- Moonen AC & Bàrberi P (2004) Size and composition of the weed seedbank after 7 years of different cover-crop-maize management systems. *Weed Research* **44**, 163–177.
- Moonen AC & Bàrberi P (2006) An ecological approach to study the physical and chemical effects of rye cover crop residues on *Amaranthus retroflexus*, *Echinochloa crus-galli* and maize. *Annals of Applied Biology* **148**, 73–89.
- Morse R & Creamer N (2006) Developing no-tillage systems without chemicals: the best of both worlds? In: *Organic Agriculture: A Global Perspective* (eds P Kristiansen, A Taji & J Reganold), 83–91. Comstock Publishing, Ithaca.
- Olofsdotter M, Jensen LB & Courtois B (2002) Improving crop competitive ability using allelopathy – an example from rice. *Plant Breeding* **121**, 1–9.
- Olsen J, Kristensen L, Weiner J & Griepentrog HW (2005) Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research* **45**, 316–321.
- Ominski PD, Entz MH & Kenkel N (1999) Weed suppression by *Medicago sativa* in subsequent cereal crops: a comparative survey. *Weed Science* **47**, 282–290.
- Pekrun C & Claupein W (2006) The implication of stubble tillage for weed population dynamics in organic farming. *Weed Research* **46**, 414–423.
- Phatak SC, Bugg RL, Sumner DR, Gay JD, Brunson KE & Chalfant RB (1991) Cover crop effects on weeds, diseases, and insects of vegetables. In: *Cover Crops for Clean Water* (ed. WL Hargrove), 153–154. Soil and Water Conservation Society, Ankeny, Iowa.

- Rasmussen IA, Melander B, Askegaard M, Kristensen K & Olesen JE (2014) *Elytrigia repens* population dynamics under different management schemes in organic cropping systems on coarse sand. *European Journal of Agronomy* **58**, 18–27.
- Rasmussen J (2003) Punch planting, flame weeding and stale seedbed for weed control in row crops. *Weed Research* **43**, 393–403.
- Rasmussen J, Mathiasen H & Bibby BM (2010) Timing of post-emergence weed harrowing. *Weed Research* **50**, 436–446.
- Rasmussen J, Griepentrog HW, Nielsen J & Henriksen CB (2012) Automated intelligent rotor tine cultivation and punch planting to improve the selectivity of mechanical intra-row weed control. *Weed Research* **52**, 327–337.
- Rasmussen K (2002) Influence of liquid manure application method on weed control in spring cereals. *Weed Research* **42**, 287–298.
- Riemens MM, van der Weide RY, Bleeker PO & Lotz LAP (2007) Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. *Weed Research* **47**, 149–156.
- Riemens MM, Groeneveld RMW, Kropff MJ *et al.* (2010) Linking farmer weed management behavior with weed pressure: more than just technology. *Weed Science* **58**, 490–496.
- Rueda-Ayala V, Rasmussen J, Gerhards R & Fournaise NA (2011) The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research* **51**, 478–488.
- Rueda-Ayala V, Weis M, Keller M, Andújar D & Gerhards R (2013) Development and testing of a decision making based method to adjust automatically the harrowing intensity. *Sensors* **13**, 6254–6271.
- Sartorato I, Zanin G, Baldoin C & de Zanche C (2006) Observations on the potential of microwaves for weed control. *Weed Research* **46**, 1–9.
- Schonbeck M, Browne J, Deziel G & DeGregorio R (1991) Comparison of weed biomass and flora in four cover crops and a subsequent lettuce crop on three New England organic farms. *Biological & Agricultural Horticulture* **8**, 123–143.
- Schwarz J & Moll E (2010) Entwicklung der Verunkrautung in Abhängigkeit von Fruchtfolge und Herbizidintensität. *Journal für Kulturpflanzen* **62**, 317–325.
- Smeda RJ & Putnam AR (1988) Cover crop suppression of weeds and influence on strawberry yields. *Hortscience* **23**, 132–134.
- Squire GR, Rodger S & Wright G (2000) Community-scale seedbank response to less intense rotation and reduced herbicide input at three sites. *Annals of Applied Biology* **136**, 47–57.
- Streibig JC, Rudemo M & Jensen JE (1993) Dose-response curves and statistical models. In: *Herbicide Bioassays* (eds JC Streibig & P Kudsk), 29–55. CRC Press, Boca Raton.
- Teasdale JR & Mohler CL (1993) Light transmittance, soil temperature and soil moisture under residue of hairy vetch and rye. *Agronomy Journal* **85**, 673–680.
- Teasdale JR & Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Science* **48**, 385–392.
- Teasdale JR, Beste CE & Potts WE (1991) Response of weeds to tillage and cover crop residue. *Weed Science* **39**, 195–199.
- Teasdale JR, Brandsaeter LO, Calegari A & Skora Neta F (2007) Cover crops and weed management. In: *Non-Chemical Weed Management: Principles, Concepts and Technology* (eds MK Upadhyaya & RE Blackshaw), 49–64. CABI, Wallingford.



- Tillett N, Hague T, Grundy AC & Dedousis AP (2008) Mechanical within-row weed control for transplanted crops using computer vision. *Biosystems Engineering* **99**, 171–178.
- Ulloa SM, Datta A, Bruening C *et al.* (2011) Maize response to broadcast flaming at different growth stages: effects on growth, yield and yield components. *European Journal of Agronomy* **34**, 10–19.
- van der Schans D, Bleeker P, Molendijk L *et al.* (2006) *Practical Weed Control in Arable Farming and Outdoor Vegetable Cultivation Without Chemicals*. PPO publication 532, 77. Applied Plant Research Wageningen University, Lelystad.
- van der Weide RY, Bleeker PO, Riemens MM, Lotz LAP, Ascard J & Melander B (2007) Tools and innovations in mechanical weed control in north-western Europe. *Topics in Canadian Weed Science* **6**, 91–102.
- van der Weide RY, Bleeker PO, Achten VTJM, Lotz LAP, Fogelberg F & Melander B (2008) Innovation in mechanical weed control in crop rows. *Weed Research* **48**, 215–224.
- Vandermeer J (1989) *The Ecology of Intercropping*. Cambridge University Press, Cambridge.
- Vanhala P, Kurstjens DAG, Ascard J *et al.* (2004) Guidelines for physical weed control research: flame weeding, weed harrowing and intra-row cultivation. *Proceedings of the 6th EWRS Workshop on Physical and Cultural Weed Control*, 8–10 March, Lillehammer, 208–239.
- Weaver SE (1984) Critical period of weed competition in three vegetable crops in relation to management practices. *Weed Research* **24**, 317–325.
- Westerman PR, Hofman A, Vet LEM & van der Werf W (2003) Relative importance of vertebrates and invertebrates in epigeic weed seed predation in organic cereal fields. *Agriculture, Ecosystems & Environment* **95**, 417–425.
- Westerman PR, Liebman M, Menalled FD, Heggenstaller AH, Hartzler RG & Dixon PM (2005) Are many little hammers effective? Velvetleaf population dynamics in two- and four-year crop rotation systems. *Weed Science* **53**, 382–392.
- Wilke BJ & Snapp SS (2008) Winter cover crops for local ecosystems: linking plant traits and ecosystem function. *Journal of the Science of Food and Agriculture* **88**, 551–557.
- Willey RW (1990) Resource use in intercropping systems. *Agricultural Water Management* **17**, 215–231.
- Williams MM, Boydston RA & Davis AS (2007) Wild proso millet (*Panicum miliaceum*) suppressive ability among three sweet maize hybrids. *Weed Science* **55**, 245–251.
- Wolf DD, Hagood ES & Lentner M (1985) No-till lucerne establishment as influenced by previous cover crop. *Canadian Journal of Plant Science* **65**, 609–613.